

**SCHOOL OF
CIVIL ENGINEERING
INDIANA
DEPARTMENT OF HIGHWAYS**

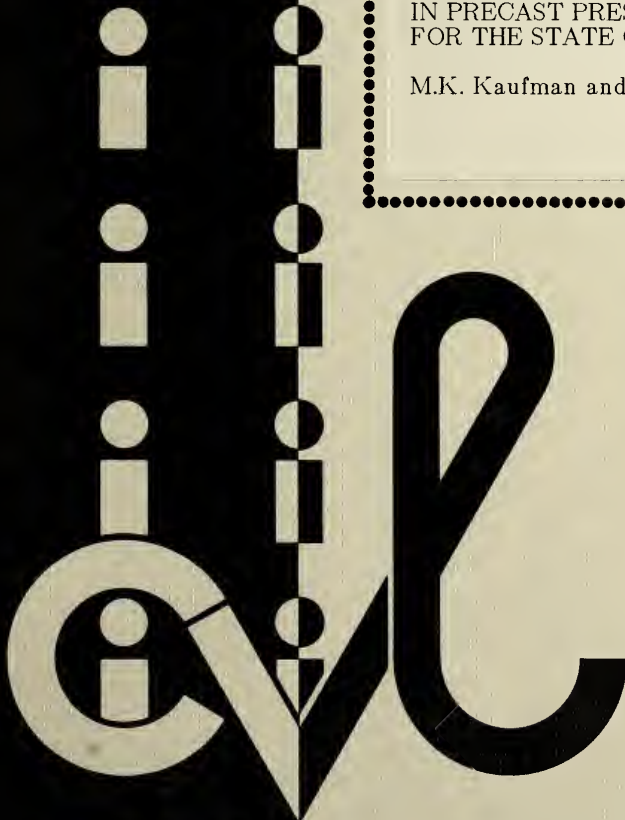
JOINT HIGHWAY RESEARCH PROJECT

Volume I/Executive Summary

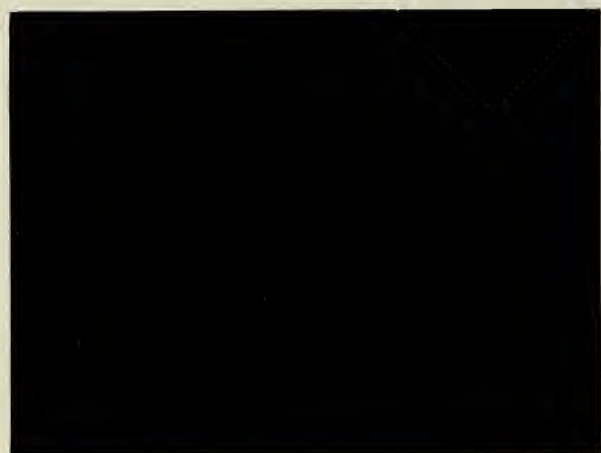
FHWA/IN/JHRP-88/5 - 2

PRODUCTION AND ENGINEERING
PROPERTIES OF CONCRETE USED
IN PRECAST PRESTRESSED I-BEAMS
FOR THE STATE OF INDIANA

M.K. Kaufman and J.A. Ramirez



PURDUE UNIVERSITY



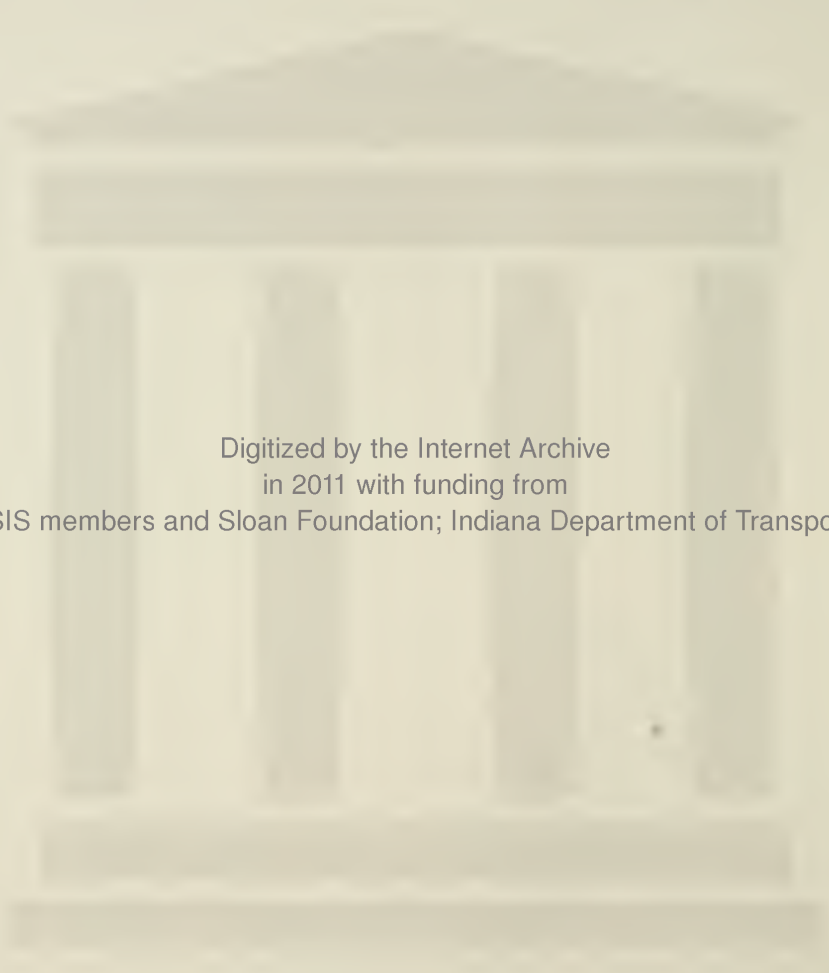
JOINT HIGHWAY RESEARCH PROJECT

Volume I/Executive Summary

FHWA/IN/JHRP-88/5 - 2

PRODUCTION AND ENGINEERING
PROPERTIES OF CONCRETE USED
IN PRECAST PRESTRESSED I-BEAMS
FOR THE STATE OF INDIANA

M.K. Kaufman and J.A. Ramirez



Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

Executive Summary

Final Report

RE-EVALUATION OF THE ULTIMATE STRENGTH AND
BEHAVIOR OF HIGH STRENGTH CONCRETE
PRESTRESSED I-BEAM SECTIONS

March 23, 1988

TO: H. L. Michael, Director
Joint Highway Research Program

FROM: J. A. Ramirez

PROJECT: C-36-56W

FILE: 7-4-23

Attached is a copy of the first of two volumes of the Final Report of the HPR Part II study "Re-Evaluation of the Ultimate Strength and Behavior of High Strength Concrete Prestressed I-Beam Sections". I have served as the Principal Investigator on this study, directed the project and have co-authored the report.

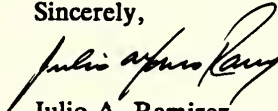
The research results reported in this first volume include recommendations to allow the use of concrete compressive strengths up to 6500 psi in the design of precast prestressed I-Beams in the State of Indiana. No modifications of the current design equations to determine the modulus of elasticity and the tensile strength are needed for the concrete currently being used in the fabrication of these members. This includes concretes with compressive strengths up to 9000 psi. The use of crushed limestone coarse aggregate is recommended in design situations where tensile stresses and deflections are critical. The recommendations are based on the results of an in-depth study conducted at a local precast plant, and a survey conducted in four other plants in the states of Indiana and Kentucky.

In the early stages of implementation it is suggested to continue the evaluation of concrete compressive strengths up to 28 days. During the winter months special attention should be given to the quality control and curing conditions for the mixes currently being used. The improper application of accelerated curing methods, and the unfavorable field curing conditions after transfer of the prestress force could lead to a reduction in the 28 day compressive strength of the concrete. During the winter months the current design mixes may need to be modified to achieve a 28 day compressive strength of 6500 psi.

The results of this study have been recommended for implementation in the State of Indiana. The use of high strength concrete in the design of prestressed I-Beams offers substantial benefits. The increased tensile strength of higher strength concretes is helpful in the service load design. Also, the increase in the modulus of elasticity results in better deflection control. The inherent relationship between higher strength concrete and better quality control makes high strength concrete attractive because of its improved long-term service performance. The qualities of high strength concrete are also proving themselves economically attractive in long span bridges. High strength concrete's comparatively greater compressive strength per unit weight and unit volume results in a reduction in dead load allowing lighter more slender bridges.

The results of this study and other findings should provide the necessary information so that designers can use higher concrete strengths to improve the economics and structural safety of bridges.

Sincerely,



Julio A. Ramirez

cc: A. G. Altschaeffl	R. A. Howden	B. K. Partridge
J. M. Bell	M. K. Hunter	G. T. Satterly
M. E. Cantrall	J. P. Isenbarger	C. F. Scholer
W. F. Chen	J. F. McLaughlin	K. C. Sinha
W. L. Dolch	K. M. Mellinger	C. A. Venable
R. L. Eskew	R. D. Miles	T. D. White
J. D. Fricker	P. L. Owens	L. E. Wood
D. E. Hancher		

1. Report No. FHWA, IN JHRP-88/5	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Title: Re-evaluation of the Ultimate Strength and Behavior of High Strength Concrete Prestressed I-Beams, Subtitle: Production and Engineering Properties of Concrete Used in Precast Prestressed I-Beams for the State of Indiana, Vol. 1		5. Report Date March 23, 1988	
		6. Performing Organisation Code	
7. Author(s) M. K. Kaufman and J. A. Ramirez		8. Performing Organisation Report No. JHRP-88/5	
9. Performing Organisation Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, IN 47907		10. Work Unit No.	
		11. Contract or Grant No. HPR-Part II	
12. Sponsoring Agency Name and Address Indiana Department of Highways State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.			
16. Abstract <p>This report describes engineering properties and current production procedures of concrete for precast prestressed I-beams in the state of Indiana. Current production techniques used in precast plants to obtain higher strength concrete are evaluated. The results of this study indicate that proper quality control and the use of admixtures have facilitated the production of concrete with 28 day compressive strength exceeding 7000 psi. A survey of 5 precast plants in Indiana and Kentucky indicated that an increase in the 28 day compressive strength requirement could be specified without major changes or additional cost to the product. Data from a year around study with field cured specimens indicated that the current empirically derived expressions to determine modulus of elasticity and tensile strength could be used in concretes with compressive strength up to 9000 psi.</p>			
17. Key Words High-Strength Concrete, Modulus of Elasticity, Tensile Strength, Compressive Strength, Curing Conditions		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 65	22. Price

**Executive Summary
Final Report**

**RE-EVALUATION OF THE ULTIMATE STRENGTH AND
BEHAVIOR OF HIGH STRENGTH CONCRETE
PRESTRESSED I-BEAM SECTIONS**

**Volume I
PRODUCTION AND ENGINEERING PROPERTIES
OF CONCRETE USED IN PRECAST PRESTRESSED
I-BEAMS FOR THE STATE OF INDIANA**

by

**M. K. Kaufman
Graduate Research Assistant
and**

**J. A. Ramirez
Assistant Professor
Civil Engineering
Purdue University**

**Project No. C-36-56W
File No. 7-4-23**

**Prepared as Part of an Investigation
conducted by the
Joint Highway Research Project
Engineering Experiment Station
Purdue University
in cooperation with the
Indiana Department of Highways
and the
U.S. Department of Transportation
Federal Highway Administration**

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

**Purdue University
West Lafayette, Indiana
March 23, 1988**

PREFACE

This is the first of two volumes on the research project, "Re-Evaluation of the Ultimate Strength and Behavior of High Strength Concrete Prestressed I-Beam Sections." This report summarizes information on the engineering properties of concrete used in precast plants manufacturing prestressed I-beams for the state of Indiana. A review of current design provisions and suggested recommendations in the use of high strength concrete for the fabrication of AASHTO I-girders are also included. The second report contains the results of nine tests on full scale Type I and Type II AASHTO I-Girders with concrete strengths over 6000 psi.

This work was conducted as Joint Highway Research Project No. C-36-56W. The study was carried out at the Purdue University Civil Engineering Structural Laboratory.

TABLE OF CONTENTS

	Page
LIST OF TABLES	iii
LIST OF FIGURES	iv
LIST OF NOMENCLATURE AND ABBREVIATIONS	v
ABSTRACT	vi
Introduction	1
Survey of Precast Plants	2
Experimental Program	5
Concrete Compressive Strength	6
Static Modulus of Elasticity	10
Concrete Tensile Strength	16
Summary	19
Conclusions	20
Recomendations	20

LIST OF TABLES

Table	Page
1 Mix Characteristics for all Batches	7
2 Compressive Strength for all Batches	8
Appendix A	
A.1 Material Properties for Batch B1	25
A.2 Material Properties for Batch B2	26
A.3 Material Properties for Batch B3	27
A.4 Material Properties for Batch C1	28
A.5 Material Properties for Batch C2	29
A.6 Material Properties for Batch C3	30
A.7 Material Properties for Batch C4	31
A.8 Material Properties for Batch C5	32
A.9 Material Properties for Batch C6	33

LIST OF FIGURES

Figure	Page
1 Modulus of Elasticity vs. Compressive Strength, Batches C1 and C2	11
2 Modulus of Elasticity vs. Compressive Strength, Batch C3	12
3 Modulus of Elasticity vs. Compressive Strength, Batches C4, C5, and C6	13
4 Modulus of Elasticity vs. Compressive Strength, Batches C1 - C6	14
5 Modulus of Rupture vs. Compressive Strength	17
6 Split Cylinder Strength versus Compressive Strength	18

LIST OF NOMENCLATURE AND ABBREVIATIONS

E_c	=	modulus of elasticity of concrete, psi.
f'_c	=	compressive strength of concrete, psi.
$\sqrt{f'_c}$	=	square root of compressive strength of concrete, psi.
f'_{sp}	=	tensile splitting strength of concrete, psi.
f'_r	=	modulus of rupture of concrete, psi.
w_c	=	unit weight of the concrete, lb per cu ft.
ϵ_o	=	strain in/in, corresponding to f'_c .
F	=	field cured concrete.
G	=	gravel coarse aggregate.
LS	=	limestone coarse aggregate.
RET	=	retarding admixture.
SUP, SUPER	=	superplasticizing admixture.
T, Tarp	=	tarpaulin cover placed during curing period prior to transfer of the prestress force.

ABSTRACT

This report describes engineering properties and current production procedures of concrete mixes for precast prestressed I-beams in the state of Indiana. Current production techniques used in precast plants to obtain higher strength concrete are evaluated. The results of this study indicate that proper quality control and the use of admixtures have facilitated the production of concrete with 28 day compressive strength exceeding 7000 psi. A survey of 5 precast plants in Indiana and Kentucky indicated that an increase in the 28 day compressive strength requirement could be specified without major changes or additional cost to the product. Data from a year around study with field cured specimens indicated that the current empirically derived expressions to determine modulus of elasticity and tensile strength could be used in concretes with compressive strength up to 9000 psi.

Introduction

Indiana Department of Highways (IDOH) Standard Specifications¹ Section 707.04(c) requires that the concrete compressive strengths for precast prestressed concrete structural members reach a minimum strength of 4000 psi at the time of prestressing and 5000 psi for the 28 day compressive strength. Precasters use different combinations of high early strength cement, high range water reducers, accelerating admixtures and accelerated curing methods to reach the concrete strength required to transfer the prestress force to the structural members. The required transfer strength is typically reached in less than 24 hours, and the producer is able to re-use the casting beds on a daily basis. The 28 day requirement of 5000 psi is often reached in 2-3 days after the cast date. Actual 28 day concrete strengths greater than 6000 psi are common; however, the use of the higher strength concrete is not common practice in the design of bridges which use prestressed I-beams in the superstructure.

As a result of the early strengths achieved at transfer, the 28 day compressive strength limit of 5000 psi is often reached in 2-3 days, and the evaluation of the concrete strength is usually not continued up to 28 days. Hence, actual 28 day strengths are not known for typical concrete mixes used in the production of prestressed I-Beams. Also, the effects of the different year around curing conditions on the engineering properties of such mixes need to be evaluated.

High strength concrete is becoming increasingly available and its structural properties should be evaluated so the designer can use them to improve the economics, and structural safety of bridges.

The following report contains information on the engineering properties of typical concrete mixes used in the fabrication of prestressed I-Beams for the state of Indiana. The information is gathered from a survey conducted on four precast plants in the states of Indiana, Kentucky, and from an in-depth study conducted at a Lafayette precast plant. The year around study conducted at the local precast plant includes information on the production as well as engineering properties of concrete mixes used in prestressed I-Beams.

The implications of allowing the use of higher 28 day design concrete strengths in pretensioned I-Beams for the state of Indiana are also discussed.

Survey of Precast Plants

Five precast plants which produce prestressed members for the state of Indiana were surveyed to obtain information dealing with their concrete production. The survey had the following objectives:

- To determine the current mixes being used in the fabrication of prestressed I-beams, and their typical 28 day compressive strengths.
- To determine the effect of accelerated curing methods during the winter months on the concrete compressive strength.

- To determine, without changing the transfer strength requirement of 4000 psi, the 28 day compressive concrete strength that could be specified without causing any major changes in current production procedures and concrete mix proportioning.

Precasters in Indiana typically use between 6.5 and 8 bags of Type III cement per-cubic yard of concrete, 3/4 inch crushed limestone as the coarse aggregate, and a variety of admixtures to obtain the desired transfer design strengths. A precast plant typically has more than one standard mix. The mix proportioning is determined from factors such as the ambient air temperature (curing conditions), time schedule and plant economics.

The 28 day compressive strength of concretes being used by the surveyed precast plants is not well known or documented. Standard practice is to load the test cylinders up to the strength specified by the design engineer. Once the specified strength is exceeded, the cylinder is unloaded without necessarily carrying the test to failure. Hence, the actual compressive strength of the elements is, in many instances, unknown. There are two reasons for this method. First, is to reduce the impact and sudden energy release to the testing machine. This reduces the wear, possible expensive repair costs and down time of the testing machine. Second, is to eliminate the brittle failure of concrete for obvious safety reasons. Also, keeping the cylinder intact allows the precasters to obtain a direct measurement of the concrete strength of a structural member at later date, and at the same time reduce the number of samples needed.

Winter time casting was also investigated in this survey. Some fabricators have indoor facilities and the cold weather has no effect on the transfer strength, but may effect the 28 day strength as the member is placed

outdoors to continue curing after the transfer of the prestress force. The precast plants that were contacted use either low pressure steam or radiant heat accelerated curing as specified in IDOH Specification 707.07.¹ Precast fabricators indicated no detrimental effects due to accelerated curing methods.

All of the fabricators indicated that the 28 day strength requirement could easily be increased. It was indicated that with proper curing conditions, the 5000 psi strength is sometimes exceeded prior to transfer of the prestress force. The question, "What could be a reasonable value of the 28 day strength?" presented somewhat of a dilemma to the manufacturers. The fabricators all said that 6500 psi would be no problem with their standard concrete mix, whether in the winter or summer months. At 7000 psi, the general consensus seemed to be that the use of a high-range water reducers or additional cement would be needed. The strength of 8000 psi and above would require special admixtures such as the use of micro-silica, fly ash or some other type of mix modification to reach the required strength at 28 days.

In summary, precast plants proportion their mixes to reach early transfer strengths. Curing conditions, time and plant economics dictate the quantity of Type III cement and the use of admixtures.

The transfer strength of 4000 psi is usually reached in less than 24 hours. This allows the producer to utilize the casting beds on a daily cycle. The 28-day requirement of 5000 psi is easily obtained in a few days because of the need of the precaster to obtain high early transfer strength.

The 28 day requirement of 5000 psi could be increased without increasing the cost of the product. All plants surveyed agreed that a 6500 psi

requirement would present no major changes to their current mix proportioning. However, the compressive strength evaluation techniques currently used by the producers do not allow for a definite 28 day requirement to be specified.

Information on the winter curing procedures indicated that there was no problem in reaching the 28 day compressive strength requirement of 5000 psi.

Experimental Program

The evaluation conducted at a local precast plant of concrete mixes used in prestressed structural members for the IDOH began in June of 1985. Many combinations of mix proportioning were evaluated. These included 6.5 or 6.9 bags of Type III cement per cubic yard of concrete, and crushed limestone or round river gravel as the coarse aggregate. The mixes evaluated also included retarding, air entraining, and superplasticizing admixtures.

Samples were taken year around. The evaluation first included compressive strength vs. time, and later expanded to the static modulus of elasticity, modulus of rupture and split cylinder tests.

Nine individual batches were evaluated. In Batches B1, B2, and B3 the concrete compressive strength versus time was evaluated. In Batches C1 through C6 the concrete compressive strength and modulus of elasticity versus time were evaluated. Tables A.1-A.9 in Appendix A contain the information and test results for batches B1, B2, and B3 and C1 through C6, respectively. The tensile strength of the concrete was evaluated for all the

batches using flexure beams and split cylinder tests.

A typical batch consisted of 6 flexure beams and 24 cylinders. The flexure beams were 6" x 6" x 18" and the cylinders 6" x 12". The flexure beams and the cylinders were cast in accordance with ASTM C31-84.⁴ Steel flexure beams and plastic cylinders with lids were used as specimen molds.

The test specimens were made after the slump and air content readings were taken. All the specimens were cast from the same batch with the exception of batch B1. Batch B1 had a variety of samples of the same mix proportioning, but from different batches. The test specimens of all the the batches were placed on the casting bed to simulate the curing environment of the precast beams. Batches B3 and C3 were steam cured up to the time of transfer. Curing conditions in the remaining batches consisted of wet burlap and tarpaulin up to the time of transfer of the prestress force.

Just prior to the prestress force transfer, the test specimens were removed from the casting bed and transported to the Purdue University Structural Laboratory located a few miles from the precast plant. The test specimens were then stripped and field cured outside the laboratory until the time of testing.

Concrete Compressive Strength

The transfer strength requirement for the 9 batches was either 3500 or 4000 psi. The 28 day requirement was 5000 psi. Table 1 summarizes the results from the 9 batches. Indiana specifications¹ require a slump between 3 and 5 inches. When plasticizing admixtures are used, the slump must be between 4 and 6 inches. The air content must be between 5 and 8 percent.

Table 1 - Mix Data for all Batches.

Mix Data				
Batch	Casting Date	Contents *	Slump (inches)	Air Content (%)
B1	6/27/85	6.9/LS/Ret/Sup	3.5-4.25	5.0-6.2
B2	7/19/85	6.9/LS/Ret/Sup	5	7.0
B3 #	11/5/85	6.5/G/Ret/Sup	5.5	5.8
C1	5/28/86	6.5/LS/Ret	3	5.8
C2	5/28/86	6.5/G/Ret	3.25	5.5
C3 #	3/4/87	6.9/LS/Ret	3.5	7.0
C4	6/11/86	6.9/LS/Ret/Sup	3.5	5.3
C5	10/2/86	6.9/LS/Ret/Sup	3	5.8
C6	4/1/87	6.9/LS/Ret/Sup	3.5	6.5

*

LS = coarse aggregate, limestone.

G = coarse aggregate, gravel.

Ret = Retarding admixture.

Sup = Superplasticizing admixture.

All Batches contain an air entrainment admixture.

6.5 and 6.9 represents the number of bags of Type III cement per cubic yard.

#

Batch steam cured prior to the transfer of prestress, all other batches field cured.

Table 2 - Compressive Strength for all Batches

Batch	Compressive Strength		
	Transfer [†] (psi)	28-Day (psi)	f'_c /age (psi/days)
B1	5700	7870	7970/56
B2	5860	7670	8710/91
B3 [#]	4830	5970	----
C1	3970	6600	7050/101
C2	4080	6440	7130/101
C3 [#]	4420	5900	6530/ 84
C4	5540	7700	8330/ 76
C5	6030	8340	8650/195
C6	5260	7530	8030/ 56

[†] Transfer times are given in Appendices B and C.

[#] Batch steam cured prior to the transfer of prestress, all other batches field cured.

All batches evaluated met these requirements as shown in Table 1. The average compressive strength at the time of transfer of prestress force, and 28 days are listed in Table 2. The results of the last set of cylinders and corresponding age are also included.

Batches C1 with limestone coarse aggregate and C2 with gravel aggregate were cast the same day. The slump, air content, and curing conditions were kept the same in these two batches to evaluate the differences between mixes with limestone and gravel aggregate. No significant difference in the compressive strengths was observed as shown in Table 2.

Batches C1 and C3 contained limestone as the coarse aggregate. Batch C3 had 6.9 bags of cement per cubic yard and Batch C1 had 6.5 bags of cement per cubic yard. Batch C3 was steam cured until the time of transfer and Batch C1 received no form of accelerated curing. The transfer strength of Batch C3, 4420 psi, exceeded that of Batch C1, 3970 psi. However at 28 days, Batch C1, 6600 psi, had a higher compressive strength than Batch C3, 5900 psi. A similar comparison can be made between Batches B3 and C2. Batch B3 differed from Batch C2 in that it contained a superplasticizing admixture and was steam cured prior to transfer. The transfer strength of Batch B3, 4830 psi, was higher than C2, 4080 psi; however, the 28 day strength of Batch C2, 6440 psi, exceeded that of Batch B3, 5970 psi.

The reduction on the 28 day compressive strength could be attributed to the steam curing; however, other variables which effect the compressive strength such as air content and slump also need to be addressed. As these two increase, a reduction of the compressive strength occurs. Even though batch C3 had a greater amount of cement than Batch C1, the values of slump and air content were also greater. Curing conditions in the field after

transfer are also important to the strength gain of the concrete. Batches B3 and C3 were cast in early November and early March, respectively. Batches C1 and C2 were cast in late May. Hence, field curing conditions for Batches C1 and C2 were much more favorable than those of Batches B3 and C3.

Batches B1, B2, C4, C5 and C6 had similar mix characteristics. These batches received no form of accelerated curing to reach the desired transfer strength. The compressive strength at the time of transfer exceeded both the 4000 psi requirement, and the 28 day compressive strength requirement of 5000 psi. The benefits from using the plasticizing admixture are shown in the compressive strengths which exceeded 7000 psi at 28 days and continued to increase to over 8000 psi. The superplasticizing admixture reduces the amount of mixing water producing a lower water/cement ratio while maintaining a workable concrete.

Static Modulus of Elasticity

The variation of the static modulus of elasticity with different concrete compressive strengths for Batches C1 through C6 is shown in Figures 1 through 4. Each data point represents the average of two modulus of elasticity measurements at a given curing time. The result is normalized for a concrete with a unit weight of 145 pcf. This is done to facilitate the comparison of these results with those obtained using Equation (1) and the Committee 362 proposed high strength Equation (2) with $w_c = 145$ pcf.

Figure 1 shows a graph of the modulus of elasticity versus compressive strength for Batches C1 and C2. A noticeable difference in the modulus of elasticity is observed when comparing the limestone and gravel mixes. The

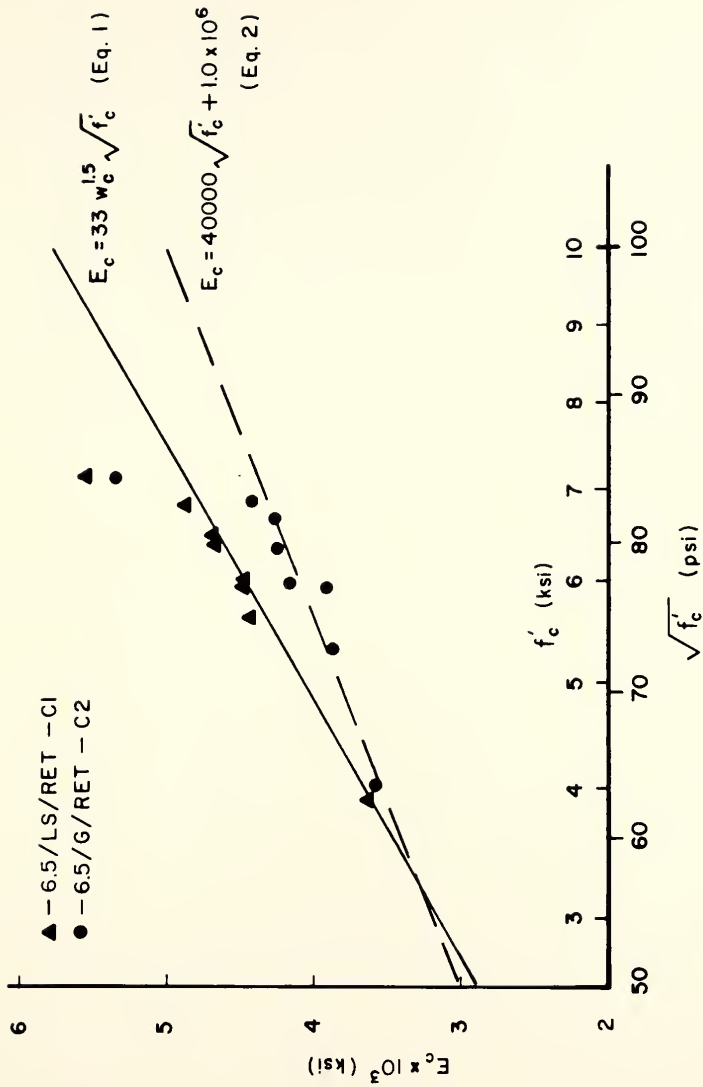


Figure 1 - Modulus of Elasticity vs. Compressive Strength, Batches C1 and C2.

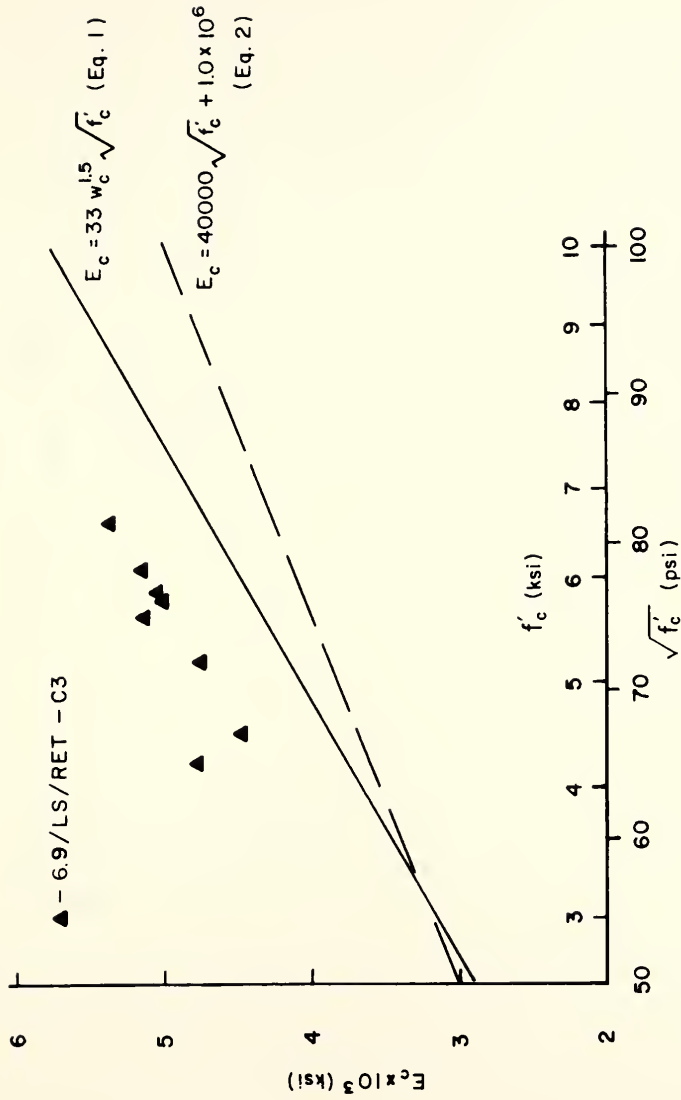


Figure 2 - Modulus of Elasticity vs. Compressive Strength, Batch C3.

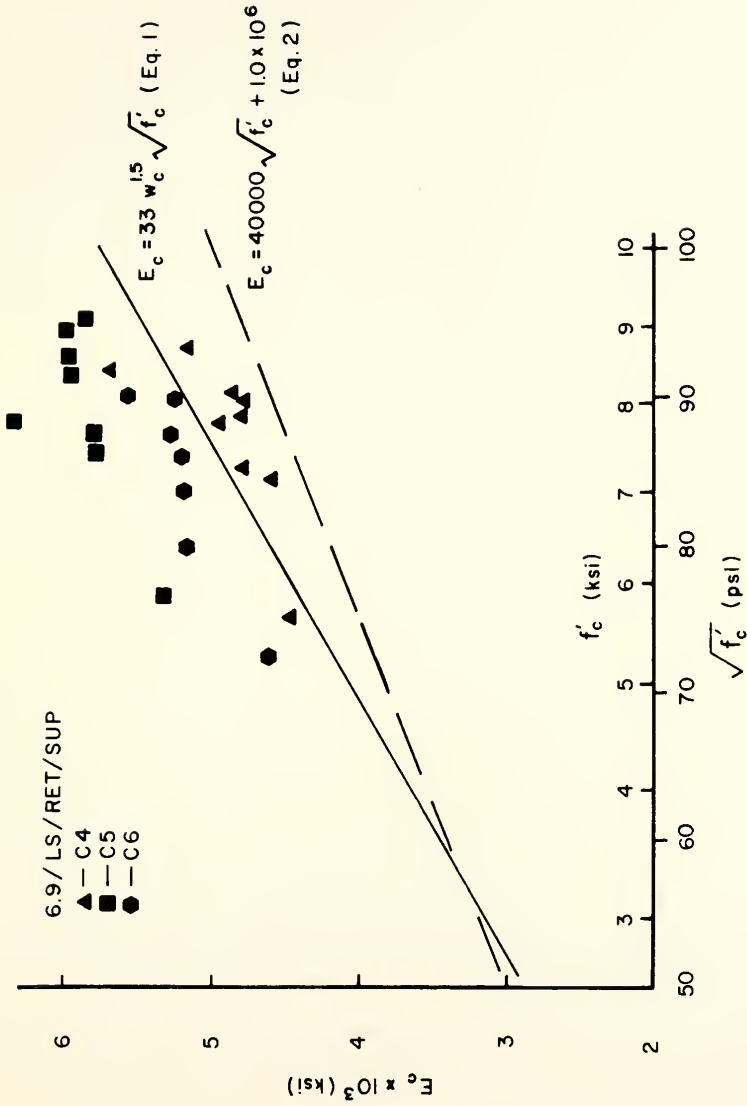


Figure 3 - Modulus of Elasticity vs. Compressive Strength, Batches C4, C5, and C6.

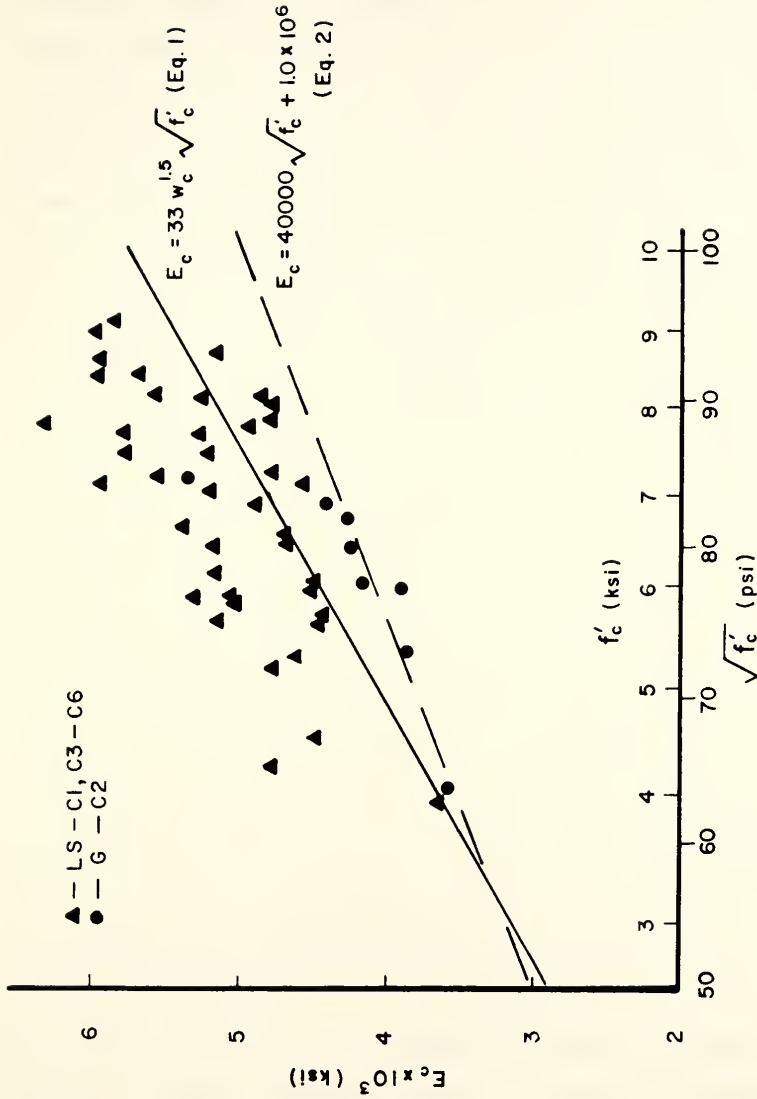


Figure 4 - Modulus of Elasticity vs. Compressive Strength, Batches C1 - C6.

limestone aggregate results in a stiffer concrete mix due to the better bond between the mortar and the aggregate. The gravel was round and had a smooth surface, while the crushed limestone had an angular shape and a rough surface. The limestone aggregate test data agrees very well with Equation (1). The gravel batch test data lies slightly below Equation (1) and agrees with the proposed high strength concrete Equation (2).

Figure 2 shows the modulus of elasticity versus compressive strength values for Batch C4. Batch C4 had a 6.9 bag mix with limestone used as the coarse aggregate. The mix was steam cured up to the time of transfer of prestress force. Figure 2 shows that Equation (1) under-estimated the measured values by an average of 15%. This difference can possibly be attributed to steam curing effects. The cast took place late in the afternoon and the local precast plant has a manually operated accelerated steam curing system. The steam was applied to the casting bed somewhere around 1 to 2 hours after completion of the cast. Batch C4 had a retarding admixture in the mix, hence steam was most likely applied prior to initial setting of the concrete. This can be quite detrimental to the compressive strength of the concrete at 28. If the compressive strength was reduced while not affecting the modulus of elasticity, this would explain the shift of the data shown in Figure 2. In other words, adding say 1000 psi to the compressive strengths would shift the data closer to the Equation (1) predicted values.

The data from batches C4, C5, and C6 are shown in Figure 3. Each batch had the same mix proportioning. The casts took place in June, October, and April, respectively. Hence, each batch was exposed to different seasonal temperatures and humidity. The compressive strengths were very similar for the batches. Equation (1) approximates the data reasonably

well.

Figure 4 combines the modulus of elasticity versus compressive strength for Batches 1 through 6. Equation (1) was determined as a best fit curve to the data shown in Figure 1. Equation (1) approaches the lower bound of the data containing limestone as the coarse aggregate and the upper bound for the mixes using gravel for the coarse aggregate. All variables considered, Equation (1) is shown to be a good empirical model for the data collected.

Concrete Tensile Strength

Shown in Figure 5 are the test data of all the flexure beam tests. Flexure beams were generally tested at transfer and at 28 days. The mix with limestone aggregate is superior to the mix with gravel aggregate. Common expressions used to predict the modulus of rupture in design applications are also shown. These values are used in stress calculations for precast prestressed members. Current AASHTO⁷ design recommendations specify $6 \sqrt{f'_c}$ as the allowable stresses after prestress losses for members with bonded reinforcement and $3 \sqrt{f'_c}$ for severe corrosive exposure conditions. Figure 5 shows that these concrete stress limits are in general below the data collected. However, Equation (4) proposed by ACI Committee 362 is shown to be an upper bound of the test data. Figure 6 shows that the limit $3.5 \sqrt{f'_c}$ is a lower bound to the data from split cylinder tests. Equation (5) proposed by ACI Committee 363 overestimates the split cylinder test data as shown in Figure 6.

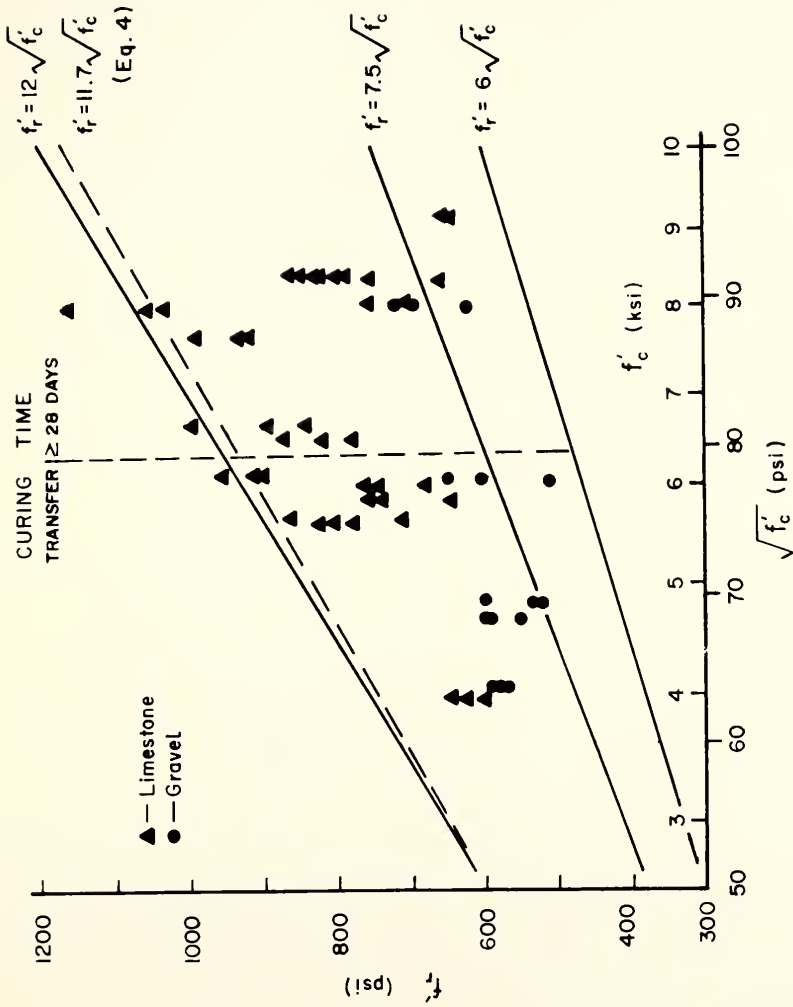


Figure 5 - Modulus of Rupture vs. Compressive Strength.

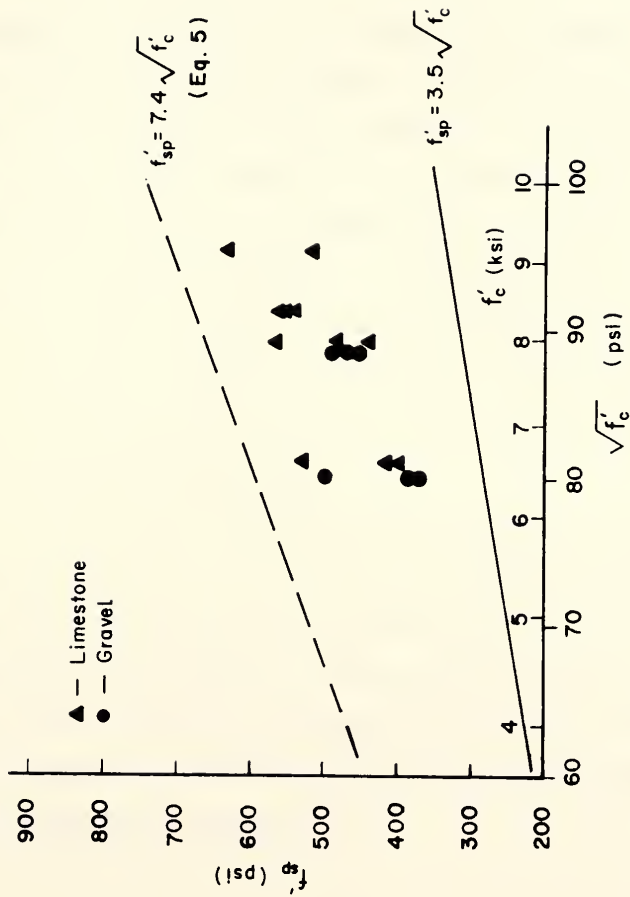


Figure 6 - Split Cylinder Strength vs. Compressive Strength.

Concrete with limestone coarse aggregate once again shows a superior tensile strength. However, more tests are needed to confirm such observation.

Summary

Proper quality control and the use of admixtures have facilitated the production of concrete with compressive strength exceeding 7000 psi in Indiana precast plants. The 28 day requirement of 5000 psi is easily exceeded with current mix proportioning. Precast plants have indicated that a 28 day compressive strength requirement of 6500 psi could be specified with no major changes or additional costs to the product. Special attention should be given to the mix quality control and curing method during the winter months. The improper application of accelerated curing methods and unfavorable field curing conditions during the winter months could lead to a reduction in the 28 day concrete strength.

Test data collected from an in-depth study at a local precast plant shows that compressive strengths in excess of 7000 psi are being produced in Indiana. In these mixes the use of limestone aggregate results in higher values of modulus of elasticity, modulus of rupture, and tensile splitting strength than those of mixes with gravel aggregate for equivalent compressive strengths. Limestone and gravel aggregates, show similar compressive strengths for equivalent mix proportioning.

Conclusions

The survey conducted in 5 different precast plants indicated that the 28-day compressive strength could be increased to 6500 psi. All the plants indicated that accelerated curing during the winter months does not present problems in obtaining the current 28 day compressive strength requirements. However, it was observed from data collected at a local plant, that there is a reduction in the 28 day compressive strength during the winter months. However, the 28 day strength requirement of 5000 psi was always satisfied.

Current empirically derived equations used to estimate engineering properties of concrete with compressive strength of less than 6000 psi can be used in concretes with compressive strengths reaching 9000 psi. The specific concrete properties evaluated were the modulus of elasticity, modulus of rupture, and tensile splitting strength.

In a following report, deflections and cracking loads obtained from nine full scale tests on AASHTO Type I and II girders will be used to further evaluate the observations of this study.

Recommendations

The following recommendations are based on the results of the in-depth study conducted at a local precast plant, and information collected from four other precast plants from Indiana and Kentucky which produce prestressed structural members for the State of Indiana.

- 1 - Allow the use of 28 day concrete compressive strengths up to 6500 psi in the design of prestressed I-Beams. During the winter

months the current mixes may need to be modified to achieve this higher strength. These modifications would be needed to compensate for the unfavorable field curing conditions, and the use of accelerated curing methods to achieve the required transfer strengths. It is also suggested to continue the evaluation of concrete compressive strengths up to 28 days. The data collected will aid in the evaluation of further modifications to the 28 day compressive strength requirement.

2 - Continue the use of the current design equations for tensile strength and modulus of elasticity of concrete for compressive strengths up to 9000 psi.

Modulus of Elasticity:

$$E_c = 33 w_c^{1.5} \sqrt{f'_c} \quad (\text{psi}) \quad (1)$$

Modulus of Rupture:

$$f_r' = 7.5 \sqrt{f'_c} \quad (\text{psi}) \quad (3)$$

3 - The use of crushed limestone as coarse aggregate is suggested when deflections and crack control are critical.

LIST OF REFERENCES

1. Indiana Department of Highways (IDOH), Standard Specifications, 1985, 601 pp.
2. ACI Committee 363, "State-of-the-art Report on High-Strength Concrete," (ACI 363R-84), ACI Journal, Proceedings Vol. 81, No. 4, July-August 1984, pp 364-411. Also, Manual of Concrete Practice, Part 1.
3. Carrasquillo, Ramon L.; Nilson, Arthur H.; and Slate, Floyd O., "Microcracking and Behavior of High Strength Concrete Subjected to Short-Term Loading," ACI Journal, Proceedings Vol. 78, No. 3, May-June 1981, pp. 179-186.
4. ASTM Standards, "Concrete and Mineral Aggregates," Section 4, Construction, Vol 04.02, 1985, 912 pp.
5. AASHTO, "Standard Specifications for Highway Bridges," Thirteenth Edition, 1983, 394 pp.
6. Pauw, Adrian, "Static Modulus of Elasticity of Concrete as Affected by Density," American Concrete Institute, Proceedings Vol. 32, No. 6, Dec. 1960, pp 679-687.
7. Carrasquillo, Ramon L.; Nilson, Arthur H.; and Slate, Floyd O., "Properties of High Strength Concrete Subjected to Short-Term Loads," ACI Journal, Proceedings Vol. 78, No. 3, May-June 1981, pp. 171-178.
8. Hansen, W., "Static and Dynamic Elastic Modulus of Concrete as affected by Mix Composition and Compressive Strength," Properties of Concrete At Early Ages, Special Publication 95, American Concrete Institute, 1986, pp 115-138.
9. Davis, R.E., Troxell, G.E., "Modulus of elasticity and Poisson's ratio for concrete and the influence of age and other factor upon these values, Proc. ASTM, 29, Part II, pp. 678-710 (1929).
10. Malhotra, V.M., "Are 4x8 Inch Concrete Cylinders as Good as 6x12 Inch Cylinders for Quality Control of Concrete?," ACI Journal, Proceedings V.73, No. 1, Jan. 1976, pp. 33-36.
11. Forstie, Douglas A., and Schnormeier, Russel, "Development and Use of 4 x 8 Inch Concrete Cylinders in Arizona," Concrete International: Design & Construction, Vol 3, No. 7, July 1981, pp. 42-45.
12. ACI Committee 517, "Accelerated Curing of concrete at Atmospheric Pressure - State of the Art," (ACI 517.2R-80), ACI Journal, Proceedings Vol. 78, No. 4, July-August 1981. Also, Manual of Concrete Practice, Part 5.

13. Hanson, J.A., "Optimum Steam Curing Procedure In Precasting Plants," ACI Journal, Proceedings Vol. 60, No. 1, January 1963, pp. 75-100.

A P P E N D I X A

Material Properties for Batches

B1-B3 and C1-C6

Table A.1 - Material Properties for Batch B1.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	June 27, 1985
Curing Method:	Tarp/Field
Slump:	3.5-4.25 in.
Air-content:	5.0-6.2 %

Cylinder Tests

Curing Time	f'_c (psi)
18 Hours	5980 5130 5160 5980 6230
26 Hours	5660 5660 6010 5340
3 Days	6860 6760 7110
7 Days	6860 6970 7360 7720 7400
14 Days	5230 6830 8060
21 Days	7920 8490 8130
28 Days	8280 7430 7890
56 Days	8030 8060 7820

Table A.2 - Material Properties for Batch B2.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	July 19, 1985
Curing Method:	Tarp/Field
Slump:	5 in.
Air-content:	7 %

Cylinder Tests

Curing Time	f'_c (psi)
18 Hours	5730 5990 5870
3 Days	6440 6190 6650
7 Days	7320 7320 7360
14 Days	6860 7040 7500
21 Days	7710 7430 7670
28 Days	7640 7600 7780
35 Days	7680 7530 7000
57 Days	8210 8170 8670
91 Days	8740 8840 8560

Table A.3 - Material Properties for Batch B3.

Mix Contents:	6.5 bag/Gravel/Retarder/Superplasticizer
Cast:	November 5, 1985
Curing Method:	Steam/Field
Slump:	5.5 in.
Air-content:	5.8 %

Cylinder Tests

Curing Time	f'_c (psi)
18 Hours	4630 4850 5020
3 Days	5060 5130 5730
7 Days	5980 5840 5800
14 Days	5450 5800 5730
21 Days	5710 5940 5890
29 Days	6470 5410 6030

Table A.4 - Material Properties for Batch C1.

Mix Contents: 6.5 bag/Limestone/Retarder
 Cast: May 28, 1986
 Curing Method: Tarp/Field
 Slump: 3.0 in.
 Air-content: 5.8 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
20 Hours	145	4030	-	-	-
	146	4000	3660	3680	0.99
	145	3890	3690	3590	1.03
3 Days	145	4880	-	-	-
	144	4850	-	-	-
	144	4780	-	-	-
7 Days	143	5590	-	-	-
	144	5380	4220	4180	1.01
	145	5900	4630	4430	1.05
16 Days	146	6080	-	-	-
	145	5940	4490	4440	1.01
	145	5940	4470	4440	1.01
21 Days	143	5940	-	-	-
	145	6080	4480	4490	1.00
	143	5870	4440	4320	1.03
31 Days	143	6470	-	-	-
	144	6650	4650	4650	1.00
	144	6690	4730	4660	1.02
42 Days	143	6400	-	-	-
	144	6400	4690	4560	1.03
	143	6650	4680	4600	1.02
56 Days	145	6930	-	-	-
	144	6900	4780	4740	1.01
	145	6790	5010	4750	1.05
101 Days	144	6910	-	-	-
	144	7060	5490	4790	1.15
	144	7170	5620	4830	1.16

Table A.5 - Material Properties of Batch C2.

Mix Contents: 6.5 bag/Gravel/Retarder
 Cast: May 28, 1986
 Curing Method: Tarp/Field
 Slump: 3.25 in.
 Air-content: 5.5 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
21 Hours	145	4100	-	-	-
	145	4030	3540	3660	0.97
	145	4100	3430	3690	0.93
3 Days	145	5060	-	-	-
	146	4950	-	-	-
	145	4490	-	-	-
7 Days	144	5520	-	-	-
	142	5410	3710	4110	0.90
	143	5270	3790	4100	0.92
16 Days	143	5800	-	-	-
	143	5910	3890	4340	0.90
	143	5980	3720	4360	0.85
21 Days	144	6230	-	-	-
	144	6190	4150	4490	0.92
	143	5770	3980	4290	0.93
31 Days	144	6580	-	-	-
	144	6440	4250	4580	0.93
	143	6300	4060	4480	0.91
42 Days	141	6330	-	-	-
	143	6930	4270	4700	0.91
	143	6790	4330	4650	0.93
56 Days	144	6500	-	-	-
	144	6470	4190	4590	0.91
	142	7000	4140	4720	0.88
101 Days	143	7060	-	-	-
	143	7320	5100	4830	1.06
	143	7020	5320	4730	1.12

Table A.6 - Material Properties of Batch C3.

Mix Contents:	6.9 bag/Limestone/Retarder
Cast:	March 4, 1987
Curing Method:	Steam/Field
Slump:	3.5 in.
Air-content:	7.0 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
20 Hours	146	4240	-	-	-
	145	4490	4640	3860	1.20
	144	4530	4210	3840	1.10
3 Days	144	5060	-	-	-
	142	3430	4540	3760	1.21
	143	5060	4800	3910	1.23
7 Days	142	4990	-	-	-
	143	5090	4560	4030	1.13
	143	5270	4750	4100	1.16
14 Days	141	5310	-	-	-
	141	5620	4790	4140	1.16
	142	5620	5110	4190	1.22
21 Days	145	5620	-	-	-
	143	5870	5020	4320	1.16
	142	5940	4790	4300	1.11
28 Days	143	5980	-	-	-
	144	5800	4920	4340	1.13
	144	5910	4980	4380	1.14
42 Days	145	6050	-	-	-
	144	6150	5030	4470	1.13
	144	6150	5100	4470	1.14
84 Days	143	6440	-	-	-
	145	6540	5470	4660	1.17
	145	6610	5250	4680	1.12

Table A.7 - Material Properties of Batch C4.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	June 11, 1986
Curing Method:	Tarp/Field
Slump:	3.5 in.
Air-content:	5.3 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
22 Hours	149	5340	-	-	-
	150	5450	4520	4480	1.01
	150	5840	4860	4630	1.05
3 Days	150	7220	-	-	-
	150	7180	5040	5140	0.98
	150	7220	4980	5151	0.97
7 Days	151	7780	-	-	-
	148	7100	4730	5010	0.94
	149	7220	4760	5100	0.93
14 Days	148	7680	-	-	-
	149	7780	5040	5300	0.95
	147	7850	4810	5210	0.92
21 Days	150	8350	-	-	-
	150	8100	4950	5460	0.91
	150	7890	5090	5490	0.93
28 Days	146	7570	-	-	-
	146	7820	5010	5150	0.97
	146	7710	4960	5110	0.97
42 Days	148	8840	-	-	-
	147	8310	4700	5360	0.88
	147	7920	5170	5230	0.99
56 Days	149	9020	-	-	-
	149	8630	5370	5580	0.96
	149	8700	5380	5600	0.96
76 Days	148	8380	-	-	-
	149	8770	6130	5620	1.09
	148	8340	5620	5430	1.03
	148	8240	5440	5390	1.01

Table A.8 - Material Properties of Batch C5.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	October 2, 1986
Curing Method:	Tarp/Field
Slump:	3 in.
Air-content:	5.8 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
18 Hours	151	6260	-	-	-
	151	5980	5580	4740	1.18
	150	5840	5620	4630	1.21
3 Days	150	7110	-	-	-
	150	6760	6060	4980	1.22
	151	7390	6490	5260	1.23
7 Days	150	7390	-	-	-
	151	7670	6700	5360	1.25
	151	7850	6760	5430	1.24
14 Days	151	7570	-	-	-
	150	7180	6170	5140	1.20
	150	7710	5970	5320	1.21
21 Days	150	7850	-	-	-
	150	7960	6600	5410	1.22
	150	7390	5520	5210	1.06
30 Days	149	8140	-	-	-
	150	8370	5920	5520	1.07
	149	8500	5900	5530	1.07
42 Days	150	9230	-	-	-
	151	9020	6260	5820	1.08
	151	8910	6450	5780	1.12
51 Days	149	9340	-	-	-
	149	9100	6000	5730	1.05
	150	8980	6010	5750	1.05
195 Days	149	8810	-	-	-
	150	8320	5800	5530	1.05
	149	8810	6240	5630	1.11

Table A.9 - Material Properties of Batch C6.

Mix Contents:	6.9 bag/Limestone/Retarder/Superplasticizer
Cast:	April 1, 1987
Curing Method:	Tarp/Field
Slump:	3.5 in.
Air-content:	6.5 %

Cylinder Tests

Curing Time	ω (pcf)	f'_c (psi)	E_{test} (ksi)	E_{aci} (ksi)	$\frac{E_{test}}{E_{aci}}$
2 Days	146	5200	-	-	-
	147	5270	4740	4270	1.11
	146	5300	4600	4240	1.08
7 Days	146	6610	-	-	-
	146	6370	5040	4130	1.22
	146	6510	5380	4700	1.14
14 Days	146	6970	-	-	-
	146	7140	5480	4920	1.11
	146	6970	5010	4860	1.03
21 Days	146	7710	-	-	-
	145	7360	5090	4940	1.03
	145	7530	5320	5000	1.06
29 Days	145	7890	-	-	-
	146	7530	5200	5050	1.03
	146	7890	5400	5170	1.04
45 Days	146	7750	-	-	-
	146	8240	5510	5280	1.04
	146	7990	5080	5200	0.98
56 Days	145	7780	-	-	-
	146	8100	5450	5240	1.04
	147	8200	5800	5330	1.09

COVER DESIGN BY ALDO GIORGINI